PARAMETRIC STUDY OF DIFFERENT PERTURBATIONS ON RINGHALS STABILITY BENCHMARK WITH RELAP5/PARCS

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Abstract

The analysis of power instabilities were tackled many years ago developing new methodologies to model this phenomena. The mechanisms underlying the causes of the power oscillations in BWR are still under study, but its consequences are well known. The simulation of the instabilities using best-estimate codes is the aim of this work.

Three dimensional time domain BWR stability analysis has been performed in Ringhals 1 NPP, using the coupled code RELAP5-MOD3.3/PARCS v2.7. In the simulation of instabilities, it is necessary to introduce some perturbations that make the power oscillate. In this work, the instabilities are induced by means of density perturbations using a new capability introduced in the neutronic code. The applied perturbation is based on the Lambda modes and their amplitudes.

This new option permits the user to perturb the moderator density in each node at each time step. Using different amplitudes for the perturbation signal the user is able to perform a complete stability analysis studying the resulting power oscillations.

1. Introduction

Since the first instability event occur in a BWR nuclear power plant, many studies has been carried out around the world to identify the mechanisms that makes the reactor power to oscillate [1], [2], [3], [4]. In some BWR nuclear power plants, oscillations were induced in order to provide experimental data. One of these tests was carried out in Ringhals 1 obtaining data at different operating points inside the zone of instabilities of the power versus core flow map. This data was disseminated to the nuclear community in the NEA Ringhals 1 BWR Stability Benchmark. [5].

Ringhals 1 is an ABB design BWR with a rated thermal power of 2270 MW and a total core mass flow of 11550 kg/s. The test data known as Record 9 of Ringhals 1 Benchmark was classified as an out of phase oscillation. Table 1 presents a summary of the core working conditions and the calculated stability characteristics for Record 9.

Table 1 Stability characteristics of Ringhals reactor for record 9

	Power (%)	Flow (%)	Stability Type	Frequency (Hz)	Decay Ratio
Rec. 9	72.6	52.4	Global	0.56	0.80
Rec. 9	72.6	52.4	Regional	0.54	0.99

In previous works [6], three dimensional time domain BWR stability analysis was performed in Ringhals 1 NPP record 9, using the coupled code RELAP5-MOD3.3/PARCS v2.7 [7], [8].

The thermalhydraulic-to-neutronic representation (mapping) was based on the fundamental and first and second harmonics shapes of the reactor power, calculated with the VALKIN code [9]. This mapping was chosen in order not to condition the oscillation pattern.

For the neutronic code, a nodalization with a 3D core mesh was modeled. The cross-sections were obtained by applying the SIMTAB methodology developed at the UPV together with Iberdrola [10].

In simulating instabilities, it is necessary to introduce some perturbations that initiate the neutron flux oscillations. In this work, a new methodology to induce instabilities in BWR NPP by means of density perturbations based on the shape and amplitude of the power modes, obtained using the VALKIN code, has been implemented in the RELAP5/PARCS. The verification of this new capability has been done using the model developed in the mentioned previous works.

The paper is organized as follows: in Section 2 the thermalhydraulic-neutronic model is described. Section 3 comprises the main part of the paper since the perturbation method is explained. In Section 4, the results are shown and discussed. Finally, the main conclusions of the paper are summarized in Section 5.

2. Description of the model

The computer code used to perform the simulations was RELAP5-MOD3.3/PARCS v2.7.

RELAP5 is a thermalhydraulic code which implements a two fluid and six-equations model to simulate the thermalhydraulic phenomena. This computer code has models for normal components of regular Light Water Reactors (LWR), like valves, pumps, heat sources, etc.

The fuel elements in the reactor core are modeled with multiple channel components. For modeling the heat transfer in the fuel, an axial-radial heat transfer equation is used. The thermalhydraulic processes are solved with six equations: mass balance, moment and energy for the both liquid phase and steam.

The Purdue Advanced Reactor Core Simulator (PARCS) solves the neutron diffusion equation with the two energy groups approach for rectangular geometries and with any number of energy groups for hexagonal geometries. With this code it is possible to obtain the 3D space distribution of neutron flux and power, as well as its temporal evolution.

For the neutronic code, the cross-sections sets have been obtained by applying the SIMTAB methodology. SIMTAB methodology provides an easy tool for properly extracting and formatting cross-sections and neutronic kinetic parameters from CASMO4/SIMULATE3 [11] to the coupled neutronic-thermalhydraulic codes. The cross section data generated for this analysis consist of 1303 different neutronic compositions considering 53 different fuel elements.

The cross-section data obtained from the SIMTAB methodology are parameterized as a function of the fuel temperature (T_f), moderator density (D_m), soluble boron concentration (S_b) and control rod insertion (α). This set of nuclear parameters is tabulated in two files, one for unrodded and the other for rodded cross-sections.

The effective Doppler temperature T_f is found from the fuel temperature at the fuel rod center T_{fc} and at the fuel rod surface T_{fs} by the relation:

$$T_f = (1-\omega)T_{fc} + \omega T_{fs} \tag{2}$$

where ω is the weighting factor, which is recommended to be equal to 0.7.

Radially, the neutronic model has been made in a one-to-one basis model, i.e., each fuel assembly has been represented with a radial node, and the core has been surrounded with reflector nodes. Therefore, a nodalization with 648 active radial nodes has been adopted. Axially, the reactor core has been modeled with 27 axial planes, two of them, one at the top and another at the bottom, considered reflector planes.

The Xenon conditions considered in the simulation are the given 3D conditions from SIMULATE-3 code.

The reactor core thermalhydraulic-to-neutronic representation (*mapping*) has been divided in four quadrants according to the first and second power harmonics (Lambda modes) obtained previously with the VALKIN code.

VALKIN is a 3D neutronic code, developed at the Universitat Politècnica de València (UPV), able to integrate the time dependent neutron diffusion equation inside the reactor core in the two-energy groups approach, using a nodal modal method. The code requires nodal cross-section values, as well as geometry and specific numeric parameters as input data. With this code it is possible to obtain the time evolution of the neutron flux and its harmonics (modes) during a transient.

Figures 1 to 3 show the first three Lambda modes calculated with VALKIN.

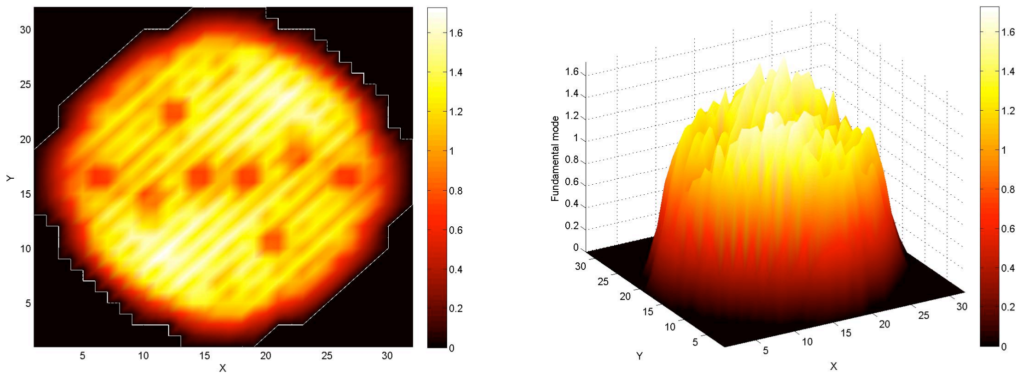

Figure 1 Planar and 3D representation of the fundamental mode.

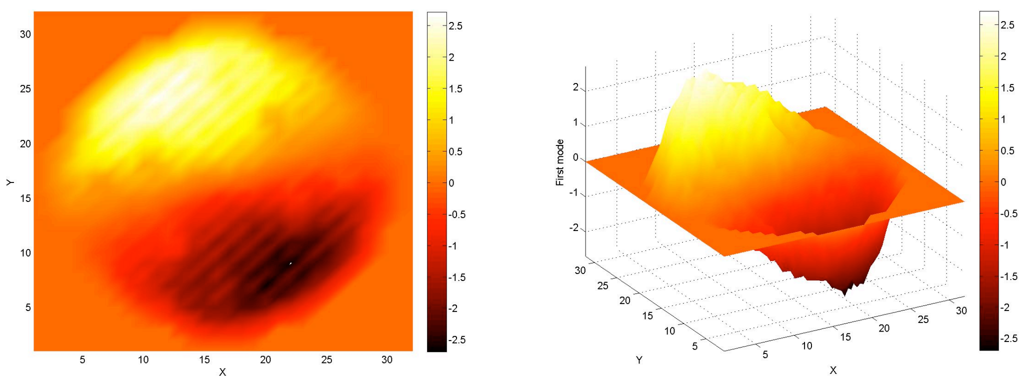

Figure 2 Planar and 3D representation of the first mode.

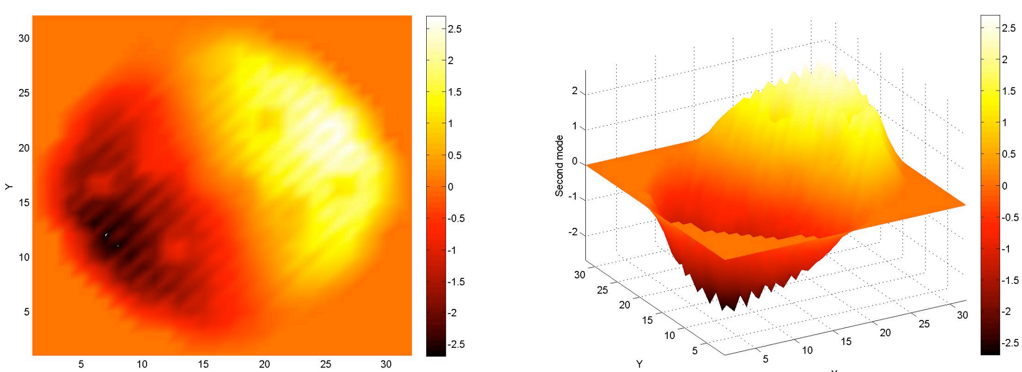

Figure 3 Planar and 3D representation of the second mode.

In RELAP5, the reactor core has been modeled with 72 thermalhydraulic channels. In Figure 4 the radial channel assignment is shown, including the bypass (channel number 250).

Fuel design characteristics have been taken from Reference 5.

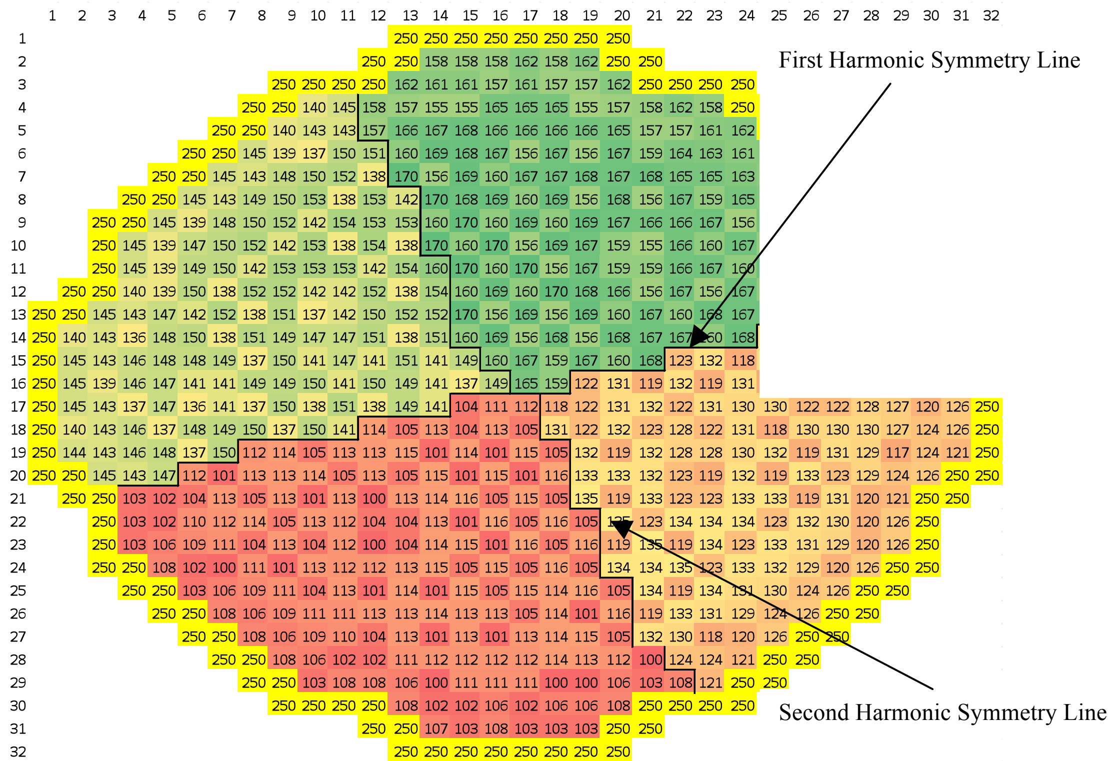

Figure 4 Thermalhydraulic channels.

The thermalhydraulic model includes, besides the reactor core, the other components in the vessel: two recirculation loops, the downcomer and the lower and upper plenums.

The downcomer has been modeled using an annulus component. Each one of the recirculation loops represents 3 recirculation pumps. Figure 5 shows an SNAP representation of the RELAP5 model.

The solution method used in PARCS v2.7 code has been the HYBRID method. This method is a hybrid Analytical Nodal Method/Nodal Expansion Method (ANM/NEM). In RELAP5 the system model is solved numerically using a semi-implicit finite-difference technique.

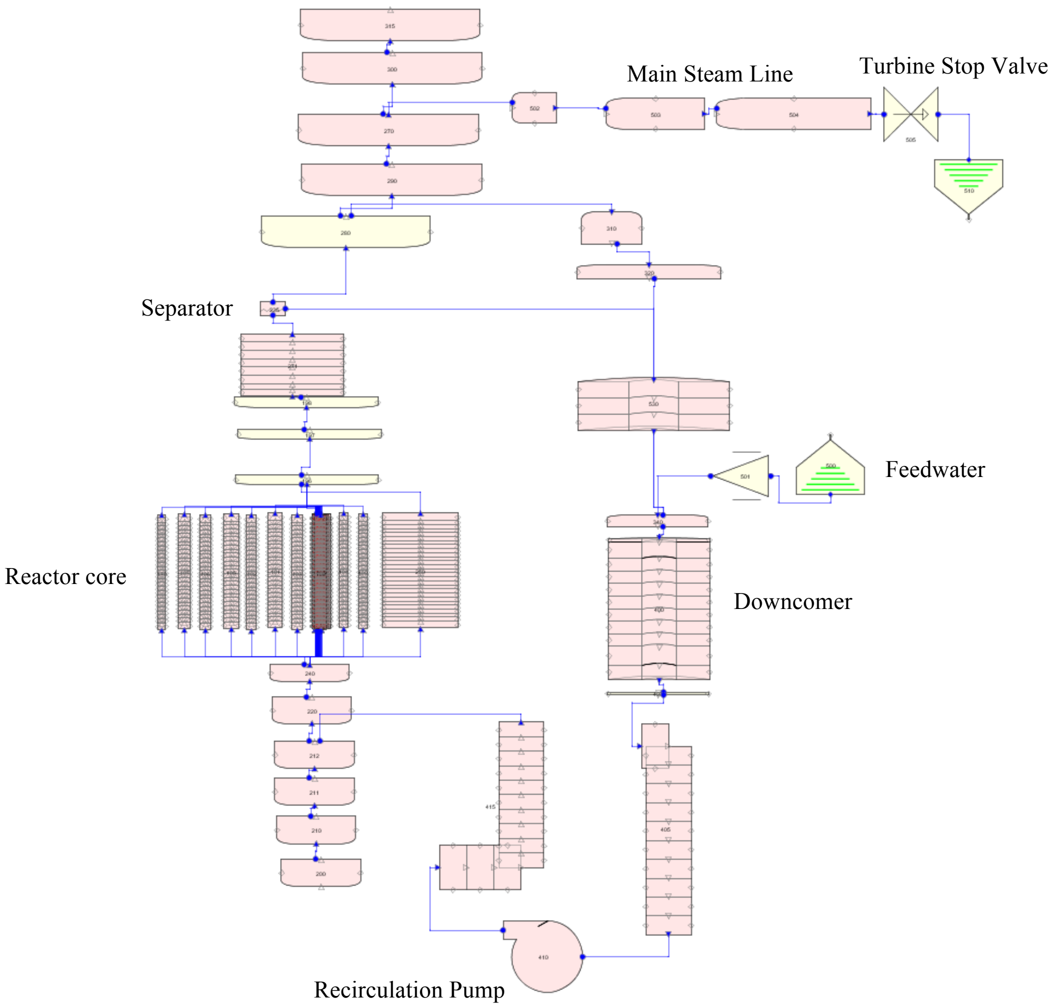

Figure 5 SNAP representation of the thermalhydraulic model.

3. Perturbation method

A new perturbation method has been developed to induce power instabilities based on the amplitudes and shapes of the Lambda modes of the neutron flux.

Since the Lambda modes were obtained previously with VALKIN code to generate the thermalhydraulic to neutronic mapping, only the modal amplitudes have to be calculated.

The signals from the Local Power Range Monitors (LPRMs) of Record 9 provided in the Ringhals 1 Benchmark documentation were used for that purpose. There are several methods to obtain the amplitudes of the modes from the LPRM signals. Two of them are the singular value decomposition (SVD) and the power modal decomposition (PMD) [12].

In this case, the modal amplitudes have been obtained by applying the SVD to the benchmark LPRM signals. The fundamental, first and second lambda modes amplitudes are shown in Figure 6.

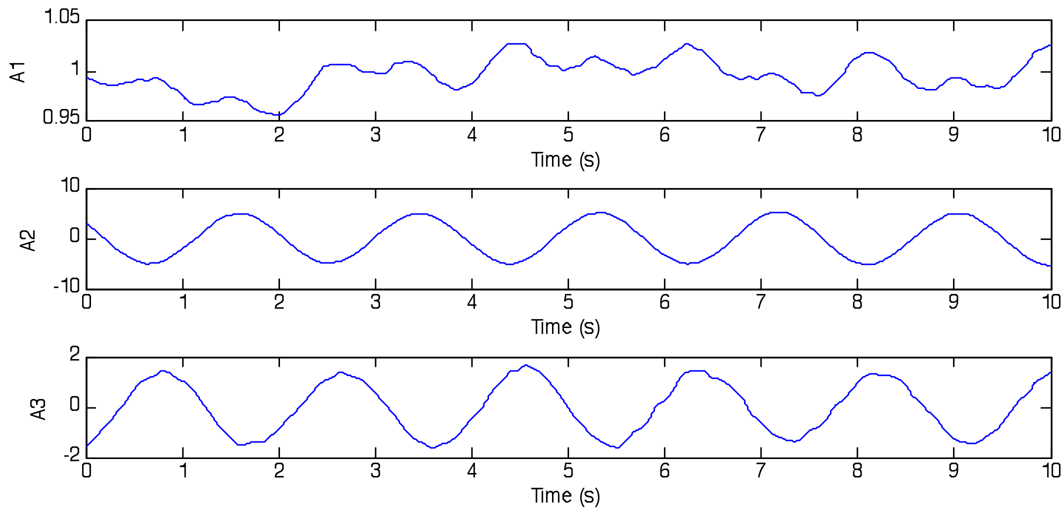

Figure 6 Fundamental, first and second lambda modes amplitudes at Ringhals Rec. 9.

This perturbation cannot be applied directly to the nodal moderator densities because it has been appeared to be very small. To be able to perturb the nodal moderator densities the amplitudes of the modes were increased by a factor of 50000.

The user can perturb only with one, two or the three modes. As it has been mentioned before, record 9 was recognized as an out-of-phase oscillation. This type of power oscillations are related to the excitation of the azimuthal modes [3] [9]. Therefore, for this study, two cases have been analyzed. In case A, first and second azimuthal modes perturbations were applied, while in case B only a perturbation to the first azimuthal was used.

In Table 2, the amplitudes applied to each mode and the equivalence in density change for the two analyzed cases are presented.

Table 2 Perturbation characteristics

	Relative Amplitude			Density Equivalence (kg/m^3)
	Fundamental mode	First Azimuthal mode	Second Azimuthal mode	
Case A	0.0	50000	50000	9.37
Case B	0.0	50000	0.0	6.10

In Figure 7, the two resulting perturbations in density are shown. The frequencies of both signals are 1.04Hz (case A) and 0.53Hz (case B) respectively.

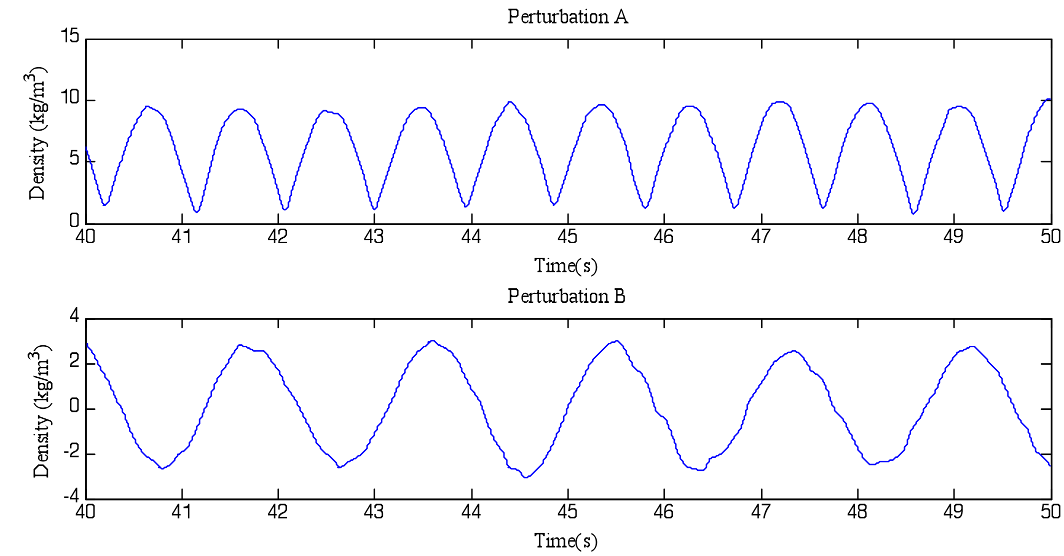

Figure 7 Relative amplitudes of the density wave perturbations.

4. Results

Figure 8 presents the power evolution during the transients. A smooth power oscillation starts at the beginning of the null transients, that is, during the first 40s any perturbation is applied.

The density perturbations are applied from seconds 40 to 50. The transient lasts up to second 100, in order to observe if the induced power oscillations are self-maintained.

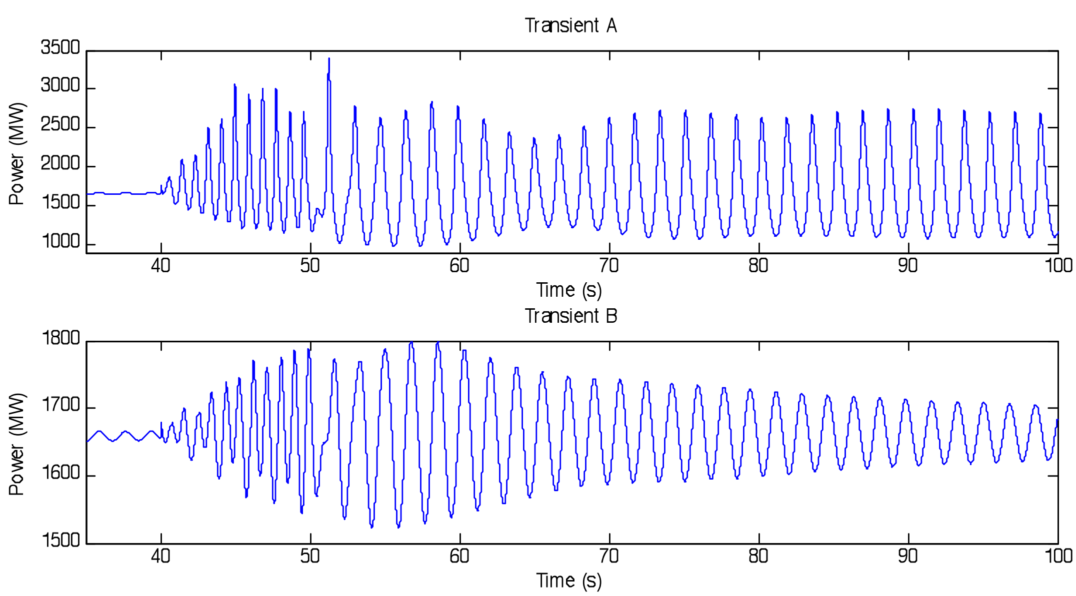

Figure 8 Total reactor power evolution.

The power evolution of the two upper and lower halves of the reactor core described by the first azimuthal mode (see Figure 2) has been plotted together. Figure 9 shows the power evolution for each of the cases. As it was expected, the two halves of the core oscillate out-of-phase.

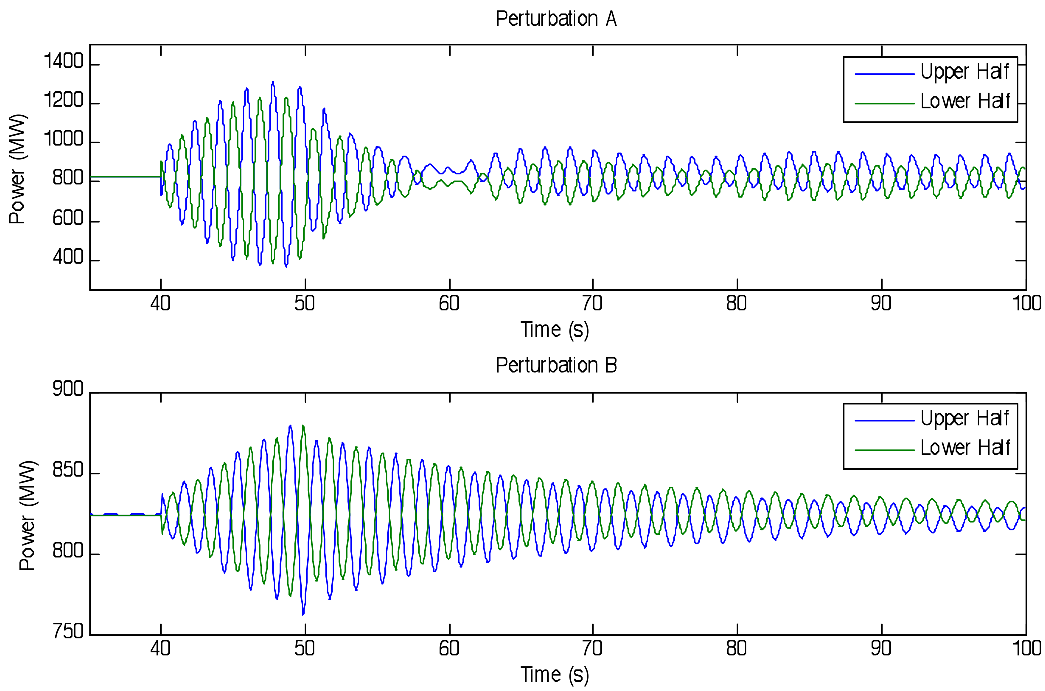

Figure 9 Power evolution of two halves of the core (upper and lower).

The neutronic code PARCS v2.7 includes an option for the calculation of the simulated LPRM signals. In order to perform a deepest analysis of the power oscillation, the simulated LPRM signals have been analyzed in certain symmetrical regions in the core. The radial position of the LPRMs in Ringhals 1core is shown in Figure 10.

There are 144 LPRMs distributed on 4 axial levels inside the reactor core.

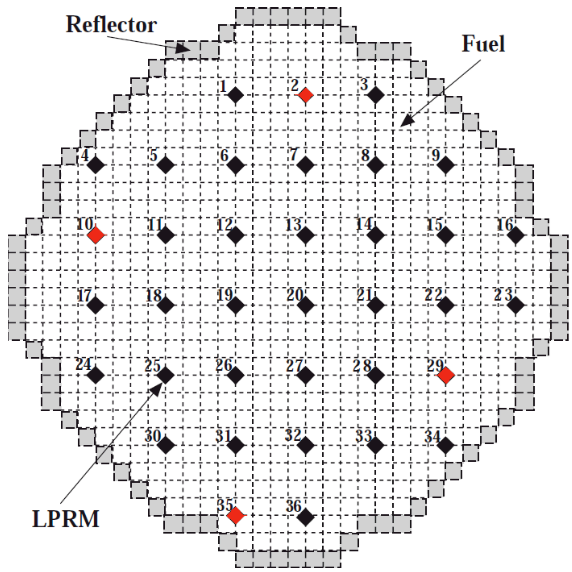

Figure 10 Ringhals 1 LPRMs radial positions.

The selected LPRMs, numbers 2, 10, 29 and 35, belong to each of the quadrants of the core (the position of these four LPRM is highlighted in red in Figure 10).

Figure 11 shows the power evolution from the LPRMs 10 and 29 for the two considered cases, A and B.

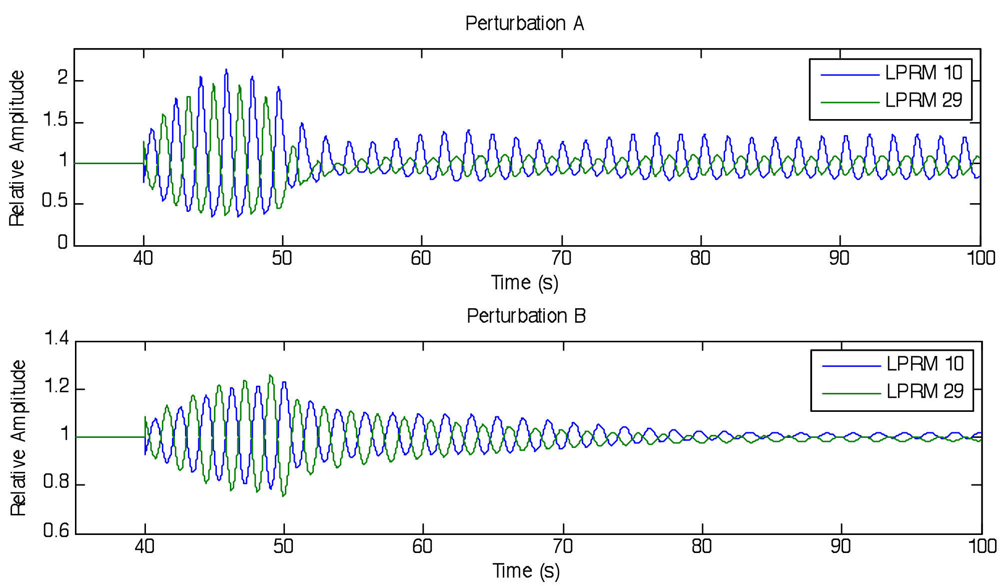

Figure 11 Normalized signal of LPRMs 10 and 29 during transients.

A better view of the power evolution from 55s until the end of the transient is shown in Figure 12:

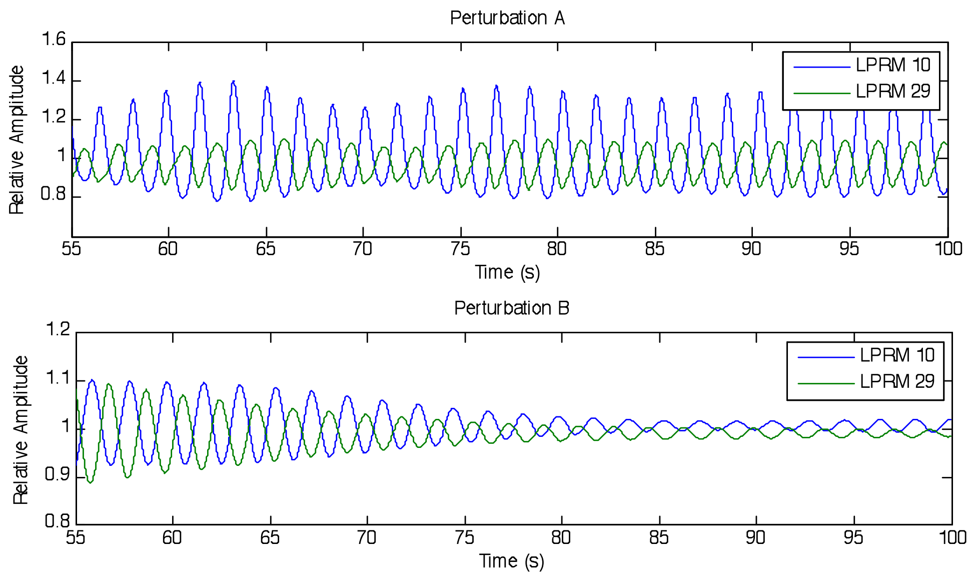

Figure 12 Normalized signal of LPRMs 10 and 29 from 55s to 100s.

In Figures 13 and 14, signals from LPRM 2 and 35 during the transient are represented.

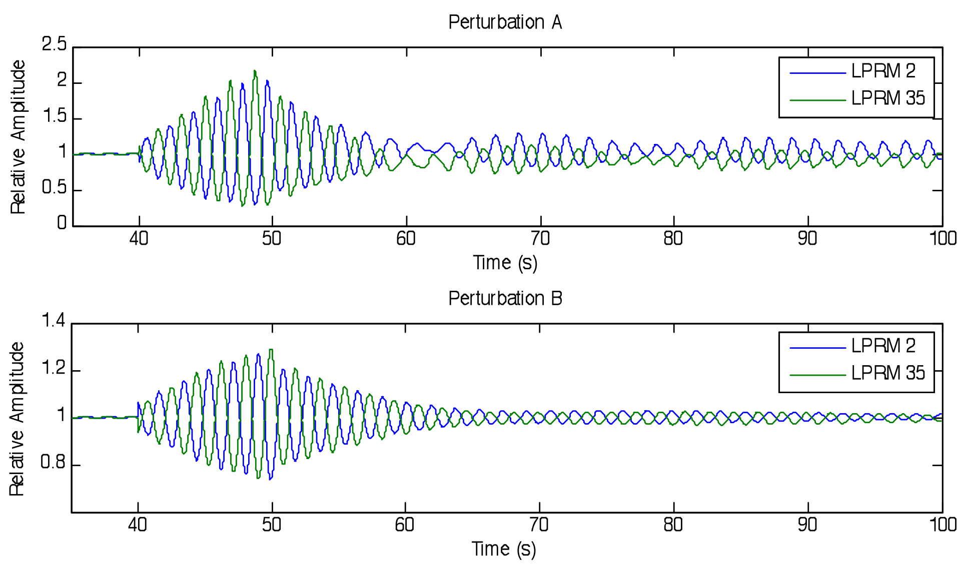

Figure 13 Normalized signal of LPRMs 2 and 35 during transients.

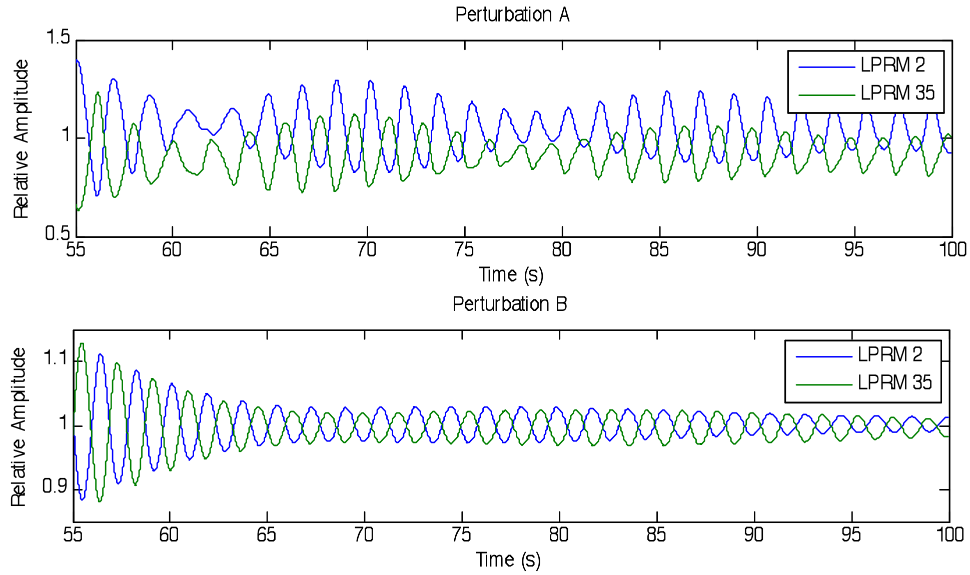

Figure 14 Normalized signal of LPRMs 2 and 35 from 55s to 100s.

In these figures we can see that the signals from LPRMs located in diagonal quadrants oscillates out-of-phase in both cases.

The singular value decomposition (SVD) of the LPRMs simulated signals has been calculated to represent the contribution of the modes to the excitation of the reactor power during the transients [11]. Figures 15 and 16 show the amplitudes of the first three power modes from 35 to 100s.

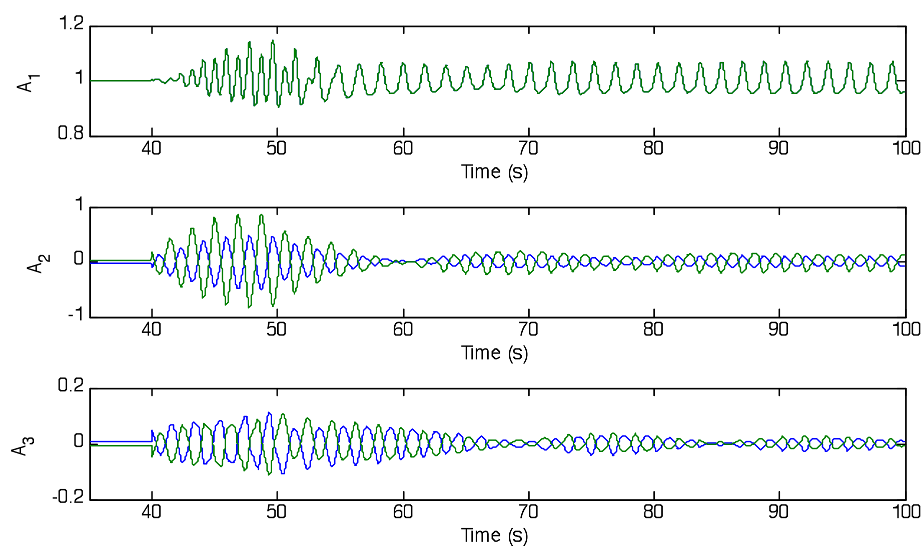

Figure 15 LPRMs 2 and 35 signal decomposition from 35 to 100s for perturbation A.

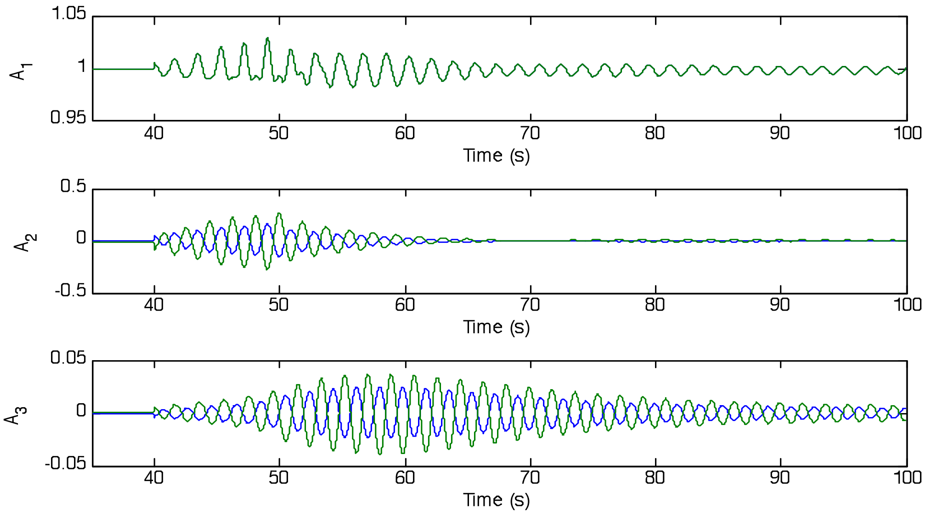

Figure 16 LPRMs 2 and 35 signal decomposition from 35 to 100s for perturbation B.

In both cases, the signal of the amplitude of the fundamental mode of both LPRMs are overlapped, i. e., they are in-phase.

The modal amplitudes show that in the case A the amplitude of the fundamental, second and third modes remain approximately constant after the perturbation, while for case B the fundamental and first azimuthal modes decay quickly and only the second azimuthal mode remain excited after the perturbation. In case A the remaining out-of-phase oscillation is due to the contribution of the first and second harmonics; while in case B it is only due to the second one.

Table 3 summarizes the frequency and decay ratio parameters of the LPRMs signals. This table shows that there is a good agreement between the benchmark results and case B results.

Table 3 Frequency and Decay Ratio of the LPRMs signals.

	Perturbation A		Perturbation B	
	Frequency (Hz)	Decay Ratio	Frequency (Hz)	Decay Ratio
Fundamental mode	0.58	0.99	0.58	0.75
First Azimuthal mode	0.58	1.00	0.55	1.00
Second Azimuthal mode	0.58	1.00	0.53	1.00

5. Conclusions

We have developed a perturbation method for analyzing the stability behavior of BWR NPP against different perturbations with the coupled codes RELAP5/PARCS v2.7.

The thermalhydraulic-to-neutronic mapping is based on the spatial shapes of the Lambda modes obtained with VALKIN code. The mapping has been chosen in order not to condition the oscillation pattern.

Results from the simulations in Ringhals 1 NPP record 9 with the coupled codes RELAP5/PARCS v2.7 show that the stability pattern depends on which mode is perturbed and the amplitudes of these perturbations, that is, the stability behavior of the reactor does not only depend on the thermalhydraulic conditions previous to the oscillation, but also to the type and amplitude of the perturbation that initiates the oscillation.

Power instabilities on a BWR system are developed by the excitation of power modes. To provoke this excitation in reactor numerical simulators, like coupled thermalhydraulic-neutronic codes, the power decomposition of the LPRMs signals can be used. Combining these decomposed signals, with different amplitudes, with the Lambda modes of the reactor power, it can obtained different oscillation patterns.

Nevertheless a parametric study of the eigenvalues and other factors to the steady state configuration, like eigenvalues separation and radial power shape could be necessary for determining thoroughly the BWR stability.

6. References

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